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The Baya Nest pavilion project: braided pattern optimization for hanging shell structures by dynamic relaxation

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Abstract

Through the study of the Baya's weaverbird nest, we carried out our research on the braided hanging shells. It is a new experimental structure that is effective in terms of low use of materials. We developed a parametrical dynamic relaxation solution to calculate principal fields of stress on every type of the hanging shell project. Thanks to experimental measurements and another dynamic relaxation algorithm that takes into account bending forces due to the braiding process, we developed a law which define a relation between density and orientation of the stems and the fields of principal stresses on an idealized continuous surface: **"each field of stress is related to an optimal braiding"**.

The apparent complexity of this method makes it restricted to researchers and engineers, thus also making it inaccessible to architects. Therefore, we sought to adapt our algorithm, making it accessible and easy to use for architects and practitioners.

The goal of this project is to make those concepts understandable for a group of architecture students and to build from scratch the set of necessary tools for the calculation, braiding optimization, designing, and fabrication of a human-scale braided hanging pavilion; allowing us to connect theoretical and practical fields. In order to popularize those notions, we engaged in three different activities:

- The development of a complete, generic, open-source and ergonomic algorithm, usable by all, for optimization of braided hanging shell using dynamic relaxation.
- The publication in La Villette editions of a collective book that compiles our study and the historical, scientific and conceptual knowledge over this subject in a pedagogic way, co-written with the master cycle students.
- The practical application of our study with the construction of a full-scale public pavilion hanging from trees in partnership with the municipality of Paris on the belvedere of the Butte du Chapeau Rouge park (Paris XIX).

Keywords: Hanging, shell, braiding, weaving, dynamic relaxation, grasshopper, optimization, teaching, pedagogy.

1. Introduction

The art of basketry goes back to the Neolithic period and is still used today. Wicker baskets, rattan furniture, lampshades made of woven blades, peach pots, grape harvest hoods, etc. Examples of everyday objects come to mind by the hundreds, but what about architecture?

The world of construction has remained quite insensitive to basketry and when it is used, it is mostly for filling purposes. Examples of structural wickerwork architecture are extremely rare. Yet habitats with braided structures exist by the thousands... in the animal world! This is the case of the nest of the Baya weaver, among others.

The objective of this study is to design a methodology for the construction of load-bearing braided shells and to apply it to the realization of human-scale pavilions suspended from the branches of trees in the park of the Butte du Chapeau Rouge in the 19th district of Paris. Its scientific contribution is to provide an answer to a question that has been imposed on us (and about which we have not found any studies in the literature): knowing the field of the main constraints of a loaded shell, is there an ideal way to braid it and, if so, what is it?

2. Nests: from reciprocal frame to braiding

2.1. Reciprocal frame structures

When we think about how a bird's nest works, reciprocal frame is the first idea that comes to mind. This structural typology forms a surface composed of inclined beams supporting each other.

It is regularly used in Japan for roof structures that do not require central pillars. The term *nexorade* is sometimes used to define reciprocal frames in which each element, occasionally called *nexor* (from the Latin node or link), is considered infinitely rigid (structure's equilibrium by reciprocity of shear forces and not by taking into account the flexural flexibility of the elements, unlike a braid for example).



Figure 1: Bird's nest and the project Uchronia by Arne Quinze.



Figure 2: Examples of reciprocal frames: model by Charlotte Gambotti, Leonardo da Vinci's military bridge, Qingming rainbow bridge, Stonemason Museum (Yasufumi Kijima arch., Yoishi Kan ing.) [credits: Kelkaku- Inc.], Exhibition Hall of the Bunraku Puppet Theater in Seiwa (Kazuhiro Ishii arch.) [credits: Kazuhiro Ishii].

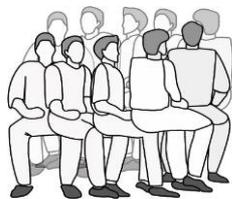


Figure 3:
Anthropomorphic
example of reciprocal
frame by Olivier
Prévost [7].

The end of each beam rests on the next beam that supports it, forming a circularly closed assembly since the last beam is finally placed on the first one. The failure of a single beam leads to the failure of the whole structure.

However, it can be objected that if a strand is removed from a bird's nest, it does not collapse, nothing very significant would happen. In addition, some birds, such as the Baya weaver, bend their blades so that each one flexes many other blades over its entire length. This method of construction is still analogous to a reciprocal structure: each blade, by its bending, presses on the blades that it interlaces with, generating a frictional force on them, and vice versa. The introduction of bending into the reciprocal structure, each element mobilizing the many other elements that intersect it, however, leads us to a new structural typology as part of this larger group of reciprocal structures: woven objects on which is based the art of basketry.



Figure 4: Baya weaver weaving his nest [DURAIRAJ].

2.2. Braiding: the art of basketry

Basketry is both an art and a craft whose product is the making of braided objects with plant blades. The terms weaving and braiding are often used, incorrectly, as synonyms. Weaving is the art of regularly interlacing textile threads in an orderly and often orthogonal pattern to create a fabric. The term braiding comes from the braid, the rope, which was made by assembling at least three fibers by repeating a pattern of crossings. In basketry the material evolves between the moment when it is braided (still green and flexible) and the period when the produced object is used (the blades will then be dry and rigid).

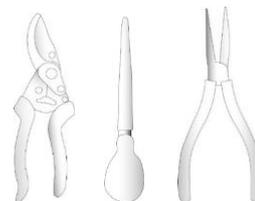


Figure 5: Basket maker's tools: pruning shears, punches, pliers.

Finally, it should be noted that the result of braiding is more likely to be a rigid surface than that of weaving, which is instead a very flexible surface. It therefore seems more accurate to describe as weaving a surface that can only resist traction (no rigidity) and as braiding a surface whose rigidity allows it to resist both traction and compression. For these reasons, and although the name of the Baya weaver obviously comes from the art of weaving, we will henceforth use the verb braid in our study.

Origins: Basketry appeared even before pottery and wood and metal working. It was used to create natural barriers to protect against animals (hedgelaying). The first traces discovered date back to the Neolithic period (negatives of braided molds on coil pottery) and the oldest-found basketry work have been exhumed in Fayum (Upper Egypt) and have been dated to more than 10,000 years ago.



Figure 6: hedgelaying [photo: Vincent Jones].

Material's choice: With the help of Roger Hérisset [4], we have chosen the materials of our study after a multi-criteria analysis, each criterion having a weighted importance (between 1 and 5).

1. Execution's easiness **M1**: from a practical point of view, braiding being a skill that requires years of specific learning process. Ours being basic, this criterion has a weight of 4.
2. Availability and provenance **M2**: Some basketry materials are difficult to find in quantity and at a reasonable cost for a project of this size. Following the traditions of French basket makers also allows to integrate the local origin of the material or not. **M2** has a weight of 3.
3. The cost **M3** = f_{yt} / C_l : as we demonstrate below, the dimensioning criterion for our suspended shell project is the tensile strength, the quantity of material to be used being inversely proportional to the tensile yield strength f_{yt} (MPa). Thus, maximizing the strength/cost ratio means minimizing the overall cost of the structure. This criterion has a weight of 5.
4. The durability **M4** = $E / (1 + k_{def})$. We are looking for a stiff material (high Young's modulus **E**) to limit the initial deformation, with a creep coefficient k_{def} as low as possible to limit the deformation under long-term loading. It is a question, therefore, of maximizing the **M4** criterion. However, the Baya project is temporary: we chose for this criterion a coefficient of 2.

This analysis, conducted on white wicker, Buff wicker, split wicker, rattan, chestnut splinters, Provence cane, bamboo blades, mulberry, hazelnut blades, rye straw and palm leaf, resulted in the selection of three materials for the project: Buff wicker, split wicker, and rattan blades.

Wicker is obtained from willow stems, which can reach up to 3 m. According to Mellgren [6], they are harvested in winter from willow stumps. There are four types of wicker. The newly harvested green wicker is not used for basketry. Wicker is raw dry when it is dried naturally by keeping the bundles upright. After drying, the bark can be removed from the stems. Either by immersing their feet in water and placing them in a high temperature room, allowing the sap to "circulate again" and the bark to detach (white wicker). Or by bathing the wicker in boiling water for three to five hours (Buff wicker). The wicker is then dried again. It will be left in water for 8 to 15 days before weaving in order to soften it.

It is also possible to split larger wicker stems into splints. The end of the strand is notched in three or four parts with a sickle, it is split along its entire length with a small wooden splitter. The ribs are finally obtained after passing through a marking gauge or an *éclisseuse*.

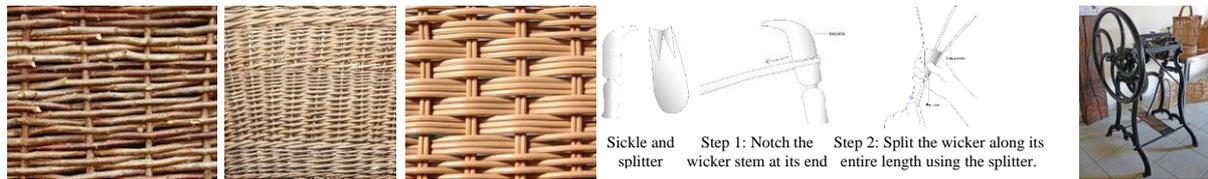


Figure 7: Dry raw, white, and Buff wicker. Wicker splitting and an *éclisseuse* [Wicker Paradise / Ji-Elle].

Rattan is also very commonly used in basketry, especially for furniture making. Its production comes from the climbing, sometimes thorny, palms; it is generally native to tropical regions. Rattan stems are between 3 and 10 mm in diameter. The palms are cut at the base, then the trunks are cut into sticks. These are removed from the leaves and thorns and dried in the sun. Using a splitter, two types of material are woven from them: the strips, or ribs, of the outer region, and the round marrow of the inside, which is used for fine basketry. For sizing, the ribs pass through a levelling machine and the pith through a die.



Figure 8: From left to right: climbing palm [Dinesh Valke], braided rattan blades, braided rattan pith, and splitter for splitting the rattan into blade and pith.

There are many different braiding techniques, the ones we have used are crocane and layered.

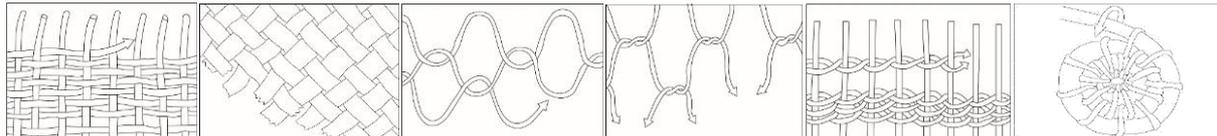


Figure 9: From left to right: crocane, layered, loop, torch, knotted and spiral wickerwork.



Figure 10: Other examples of weaving in nature: social republicans [Diego Delso, delso.photo, License CC-BY-SA], weaver ants [Frawsy Eklablog & Bernard Dupont] and caciques [Tanguy Deville].

Basketry applications can be found in primitive or vernacular habitat. In Ethiopia, in the Guge mountains, members of the Dorze tribe weave ogive-shaped huts with false banana palms on frames made of bamboo and stems of local timber. The structure is lightweight and can be lifted by three or four people to be moved. They are initially built very high, about 10 to 12 meters because of the presence of termites that destroy, by devouring them, the bases of the huts whose height then gradually decreases in time! This habitat has an average lifespan of 60 years and can last up to 80 years.

The Molo tribe from Lake Turkana in Kenya, use acacia wood, grass or dried wood fibers to build their spherical-shaped huts. The hut is composed of a structure made of acacia branches on which is braided a cover of palm leaves and dried wood fibers. Some of the huts are raised by pilings to prevent pests.



Figure 11: Dorze huts, Chench village, under construction [Kevin Smith], and Molo huts, Turkana Lake [Eric Lafforgue, Bjorn Svensson / Alamy Banque D'Images / Richardandmarthashaw.blogspot.com].

Some examples are also to be mentioned in modern architecture. However, all of them, with few exceptions, have in common that braiding is only used as a filling element, it is not structural.



Figure 12: Ephemeral Beaubourg project built by Nikolay Polissky in the Nikola-Levinet park (Kaluga region) and bamboo tunnel by Wang Wen Chih [Cave Urban]. Weaver's Nest project by Porky Hefer of Animal Farm (South African materials and manufacturing techniques on steel frames) and another project from the same design office [Deezen & Animal Farm].

3. Design of the “BAYA” algorithm

Our goal is to transpose the basket maker's skill to an architectural work. Our project, Baya, is a suspended pavilion, but our thinking is broader: it must be applicable to any loaded surface, such as shells, as well as simpler elements like beams.

These elements constitute the entire structure of the work. The loads circulate through the entire thickness of the structural surface of the shell and subject it to tensile and compressive stress. Our problem is to study these constraints fields and to question the existence of an optimal braiding of the shell in relation with them. This study consists in observing the behavior of the stems, on a 30*30 cm specimen, and understanding the relations between the geometrical characteristics of the braid and its mechanical behavior when it is subjected to a given loads field in order to feed an algorithm, called BAYA, capable of giving the optimal braiding of any shell under various loading cases. Ergonomic and open-source, it will be available on the site www.construire-l-architecture.com.

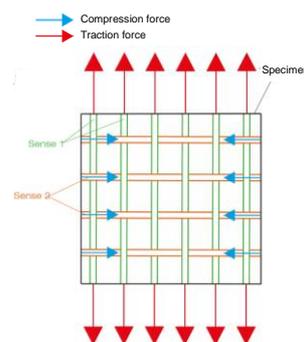


Figure 13: Diagram of a braided specimen subjected to a given stress field.

3.1. The laws of optimal braiding

Methodology: our numerical simulation is conducted by dynamic relaxation, a method that allows us to solve static equilibrium problems by a fictitious dynamic calculation. Bouhaya [1] explains that the objective is to find the equilibrium position of a structure subjected to a set of loads by a pseudo-dynamic calculation : “it is an iterative method that describes the movement of the structure from the moment of loading to its equilibrium (...)” and, “according to [Barnes], “the basis of the method is to trace step-by-step for small time increments, Δt , the motion of each node of a structure (from an initial disturbed instant) until, due to artificial damping, the structure comes to rest in static equilibrium.” A more complete pedagogical presentation of dynamic relaxation applied to elastic gridshells (ELASTICA algorithm) is given by Leyral *et al.* [5] in another paper of IASS 2021.

In a braid constrained in the plane, we observe three types of forces: the forces due to the bending of the strands that one must bend to pass above and then below the strands of the other layer, the restoring

forces related to the axial deformation of the strands (Hooke's law) and the friction forces at the knots. Knowing that we can simulate the latter by looking at the normal stress (by Hooke's law) in fictitious bars connecting the two directions at each node, only Hooke's law and the bending force are thus necessary to simulate the behavior of a braid. These are therefore the same forces that are found in the dynamic relaxation of elastic gridshells (whose own weight would be neglected).

From this observation, the choice was made to take over the core of the ELASTICA algorithm, by modifying it so as to be able to study the reaction of a braided specimen subjected to a field of principal stresses in compression and tension. The objective is to understand the influence of the different braiding parameters listed below.

The material (fixed setting): the experiment is conducted on two of the materials used in the Baya project: round wicker stems and thin rectangular rotten stems. They are modeled by their geometrical and mechanical characteristics: the dimensions of the cross-section of the strands, the modulus of elasticity $E= 3000$ MPa and the elastic limit stresses in tension and compression $f_{yt} = f_{yc} = 25$ MPa.

Input parameters: specimen geometry and external loading. The braid is a set of strands, braided in two different directions. In each direction, the strands are parallel to each other, and pass alternately above and below the strands of the other direction.

The specimen is subjected to forces that simulate the principal stress field in the shell (it represents two directions of orthogonal stresses at the level of the considered finite element, which has been oriented to only have normal stress components).

The simulation of the different principal stress fields therefore depends only on the two following parameters:

- **Traction / Compression.**
- **The value $F_{\sigma 1}$ and $F_{\sigma 2}$ of the efforts (N/ml) respectively in direction 1 and direction 2 ($|F_{\sigma 1}| \leq |F_{\sigma 2}|$).**

Once the material is fixed, the geometry is defined by four parameters:

- The braiding densities n_1 and n_2 of each layer (in number of strands per ml)
- The orientation α of the braiding with respect to the principal stress field (angle of the layer 1 with the orthogonal forces applied on the specimen).
- The angle θ of braiding: angle between the two layers of braiding.

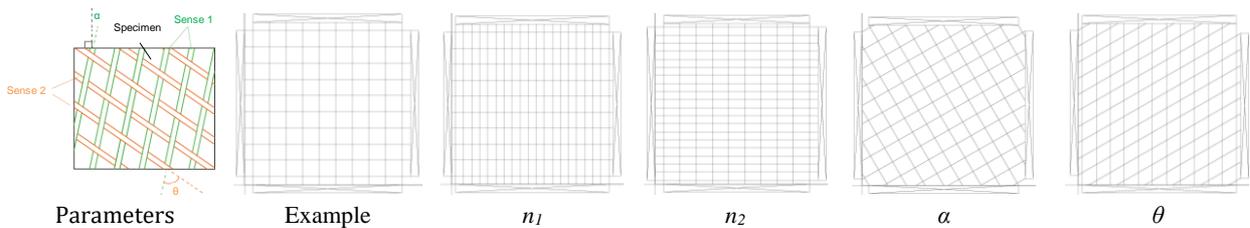


Figure 15: Input parameters on the geometry of a braided specimen.

Table 1: Input parameters and test steps.

Input parameters	Symbol	Unit	Range of variation	Step
Value of force 1	$F_{\sigma 1}$	N	150 - 10000 N	1000 N
Value of force 2	$F_{\sigma 2}$	N	100 - $\text{Min}(F_{\sigma 1}; 4000\text{N})$	500 N
Braiding density in direction 1	n_1	u/ml	10	n/a
Braiding density in direction 2	n_2	u/ml	10	n/a
Braiding angle	α	Degrees (°)	0 - 45°	5°
Orientation of the braid in the specimen	θ	Degrees (°)	0 - 45°	5°

After each simulation, several outputs are collected and combined for failure criteria comparison.

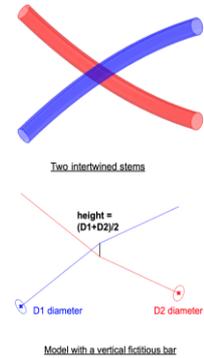


Figure 14: Fictitious vertical bar simulating friction forces at a knot.

Table 2: Outputs and criteria controls.

Output	Symbol	Unit	Controls	Criteria
Max tensile strength in strands	T_{max}	N	V1 – Yield strength	$T_{max} \leq f_{yt}$ and $C_{max} \leq f_{yc}$
Max compressive strength in strands	C_{max}	N	V2 – Buckling	$C_{max} \leq \pi^2 EI / l_{mesh}^2$
Maximum axial force differential between who consecutive strands	ΔN_{max}	N	V3 – Knots no-translation	$\alpha' \cdot V \leq \Delta N_{max}$ with α' the friction coefficient
Maximum strength in fictitious bars	V	N	V4 – Knots no-rotation	$El \cdot \sin(\rho) / l_{mesh} \leq \alpha' \cdot V \cdot R$ with ρ = angle between 2 strands; R = radius of the contact surface
Maximum displacement	d	mm	V5 – Global buckling	Kinetic energy has converged + specimen is still planar

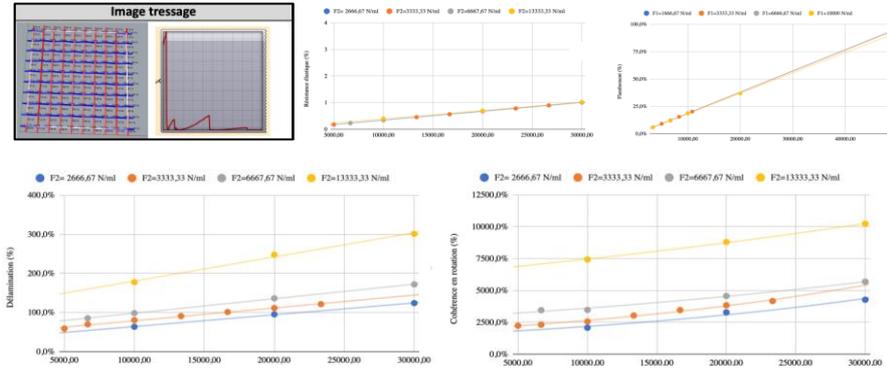


Figure 16 – Test’s results and criteria charts examples: V1, V2, V3, V4 as $F_{\sigma 1}$ functions; each line corresponding to a different $F_{\sigma 2}$ value).

The study of the specimen teaches us the following principles:

- As expected, the yield ratio T_{max} / f_{yt} is a linear function of the tensile strength $F_{\sigma 1}$
- Local buckling (C_{max} compared to Euler’s force) is not an issue with regular n_1 and n_2 densities
- Global buckling (non-planar specimen) depends mainly on compressive strength $F_{\sigma 2}$
- Friction forces raise with $F_{\sigma 1}$ and fall with $F_{\sigma 2}$; which explains why instability failure appears with lower compression values when tension is not high enough (cf. second chart)
- High values of $F_{\sigma 2}$ lead to knots translation or rotation, even negative friction (decompression)
- Positive friction force possesses a physical limit (depends on the diameter of strands)
- Changing the braiding angle θ has little effect if input forces are almost parallel to the strands (α close to zero); which validates the idea of braiding along the principal stresses.

3.2. BAYA algorithm for optimal braiding of architectural shells

The BAYA algorithm determines the principal stresses for any shell under a given load. Thanks to the above optimal braiding laws, it is able to give the ideal braiding for the shell. Algorithm can be applied to any loaded surface, including basketry items such as baskets, we have chosen to illustrate its presentation on an isostatic beam on two supports loaded by a uniformly distributed force.

1. Geometry of the studied shell: The shell surface, the position of the support points and the loads are the input data of the BAYA algorithm.
2. Finite element mesh of the shell: The surface is discretized into small rectangular isosceles triangles, each representing a finite element of it.
3. Obtaining efforts: in the finite element edges by dynamic relaxation.
4. Obtaining the principal stresses: deduced from the forces by rotation of stresses’ coordinate system on the largest support reaction of the right-angled isosceles triangle.
5. Braiding of the shell: by using the laws defined above.

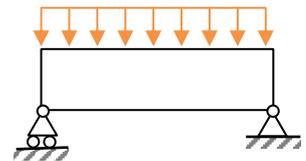


Figure 17: Diagram of the beam to be braided.

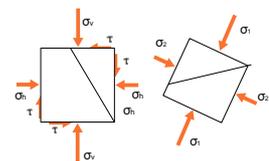


Figure 18: Principal stresses on a finite element.

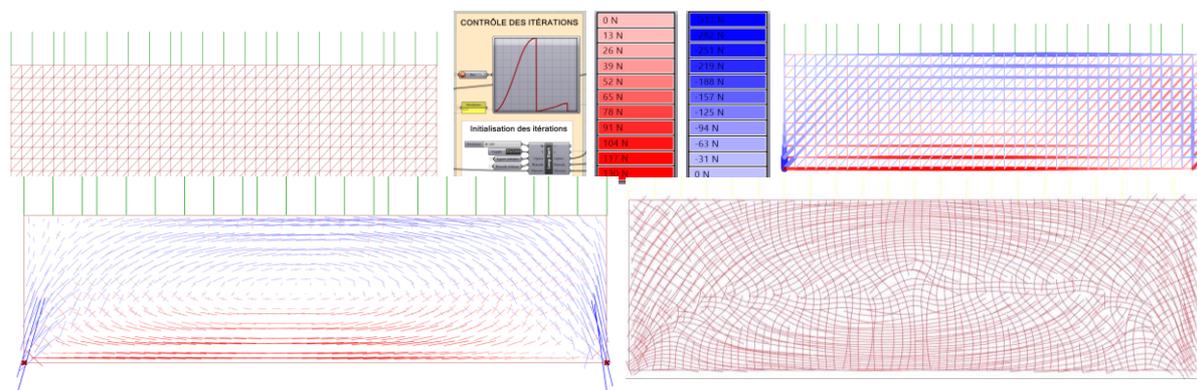


Figure 19a: Meshing, strains and principal stresses, and optimal braiding by the BAYA algorithm.

The predominant mode of failure of a suspended nest is due to the breaking of the strands. We lead the verifications in the elastic domain with a safety factor on the results of the calculations taking into account various parameters: variations in modulus of elasticity E (between the different blades, due to moisture and due to creep), accuracy of shape of shell, variations in loading, accuracy of computer model and assumptions, nature and significance of collapse and consequences of failure. Our global safety factor is 6.30 (4.50 x 1.40 security coefficient on ULS combination).

4. Experimental verifications

4.1. Comparing BAYA to Pratt

In the making, the braiding algorithm was tested on a 2D rectangular surface since the principal stresses of a uniformly loaded isostatic beam are familiar (see Figure 19a).

Further to this test, we decide to braid the result, in order to compare our “Baya beam” to a Pratt truss made out of stacked and connected stems. For identical sizes, loads and safety factors, Baya needs half the quantity of Pratt.

This will soon be verified by loading the two specimens up to failure.

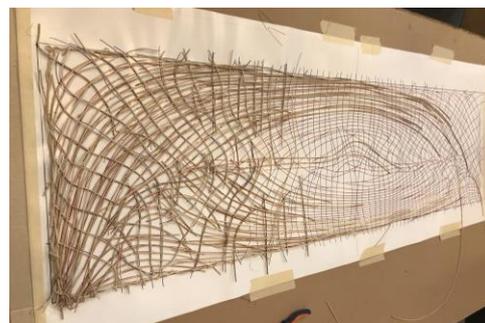


Figure 19b: Braided beam according to Baya laws (in progress)

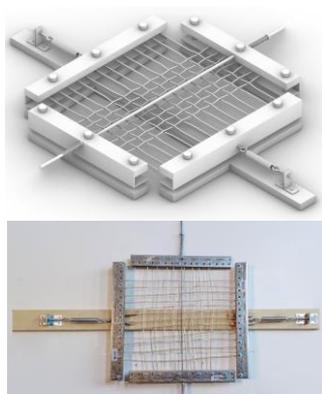


Figure 20: Experimental device.

4.2. Laws of optimal braiding by studying physical specimens

The numerical model idealizes reality, and several simplifying assumptions were made for the verifications. As the results could not be compared with the bibliography, since we did not find any equivalent studies, it was necessary to verify them by a similar experimental study.

The preliminary results of this physical experiment, which is still in progress, tend to confirm, with a satisfactory margin of accuracy, those of the numerical model.

4.3. Principal stresses

4.3.1. Photoelasticimetry

Light is an electromagnetic wave whose electrical component propagates orthogonally to its magnetic component. This polarization can be modified by a polarizer placed downstream of the light source, which transforms the light wave into a linearly polarized wave. If we place a second polarizer, called an analyzer, after the first one, all the light coming out of it will be transmitted if their axes are parallel, and no light will come out of it if they are perpendicular.

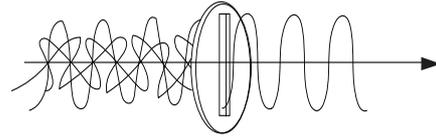


Figure 21: Polarizer principle

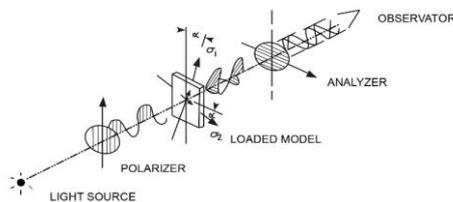


Figure 22: Plane polariscope principle.
[https://cours.polymtl.ca/]

Some materials are birefringent when subjected to stress: they are capable of polarizing light along the axes of the principal stresses within them. This is the principle of photoelasticimetry.

Plane Polariscope: a birefringent material is placed between a polarizer and an analyzer, we obtain an experimental device called a plane polariscope. It can be shown that the light intensity at the output of the experimental device is equal to

$$I = a \cdot \sin^2(2\alpha) \cdot \sin^2 \left[\frac{\pi \cdot c \cdot d}{\lambda} (\sigma_1 - \sigma_2) \right] \quad (1)$$

α is the angle between the principal stresses and the angle of the polarizer. When $\sin^2(2\alpha) = 0$, the light intensity is equal to zero and a black band is observed: these are the isoclines. Along these isoclines, the stresses are parallel to the angle of the polarizer. To obtain the lines of the principal stresses, called isostatics, we thus draw the isoclines for different angles of the polarizer, place the directions of the principal stresses σ_1 and σ_2 on them and then connect them.

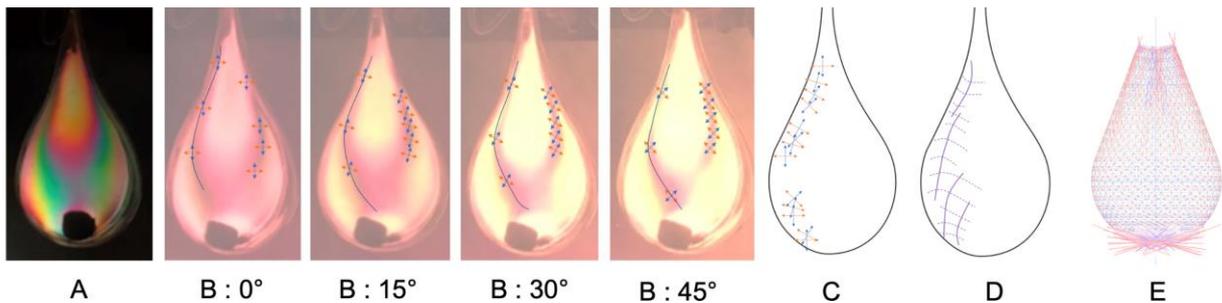


Figure 23: Isochrones for one specific load (A), isoclines drawn for various polarizer angles (B), merged drawings (C), isostatics (D), comparison with the principal stresses from the algorithm (E).

4.3.2. By photogrammetry on a physical shell

A suspended balloon is filled with water (pretension gives the shell compression capacity) and loaded with a mass. A picture analysis algorithm recognizes marker points; then Hooke's law converts the grid deformation into strengths.

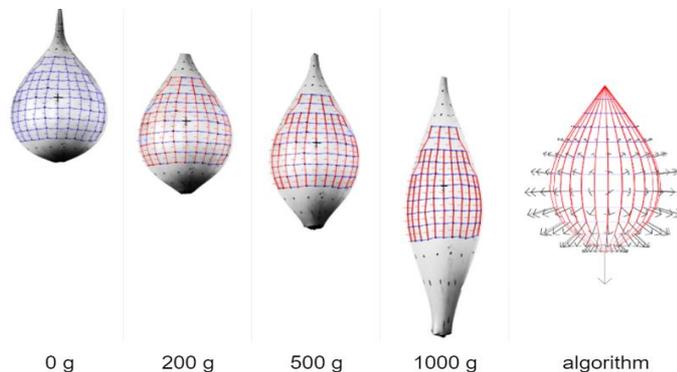


Figure 24: Photogrammetry compared to algorithm results.

5. Applications

5.1. Study of the of the Baya weaver's nest

5.1.1. The Baya weaver

The Baya project, described below, is a colony of suspended pavilions whose skin, the very structure of the object, is a braid of long and fine elements. It echoes many habitats of the animal world, in particular bird nests. Among them it appeared to us that the one of the Baya weaver was an object particularly close to our intention.



Figure 25: Studied Baya weaver's nest.

The Baya weaver (*Ploceus philippinus*) is a small bird of the *Ploceidae* family, which lives in Southeast Asia and builds suspended nests in the shape of weighted down stockings (close enough to a drop of water). The etymology of its name comes from the Sanskrit word *vaya* meaning the one that weaves. Most of the colonies (50 to 100 nests in general) are in India, on coconut trees in the northeast and thorny trees in the southwest.

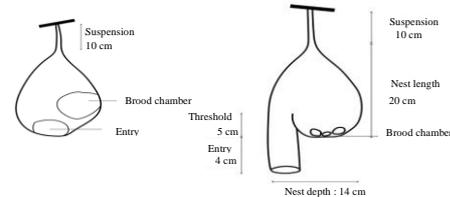


Figure 26: General architecture of a Baya weaver's nest according to Quader [8] at the helmet stadium and at the final stage.

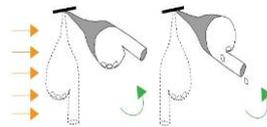


Figure 27: Davis' hypothesis [3] of its orientation to the wind with respect to the risk of egg fall.

The weaving of the suspended nest begins during its reproduction period, the period of rains associated with the monsoon, caused by an unidirectional exchange of warm air loaded with humidity moving from the ocean to the land. The nest serves to protect the bird, its eggs and young from predators and the climate. The location of the tree (overhanging the water to limit the entry of rodents), its species (thorny trees are preferred), the position of the nest on it (on the side protected from the wind), and its orientation are thus judiciously chosen. The nest, composed of 1.000 to 1.500 long strands of 20 to 60 cm, is braided during eighteen days for breeding purposes.

Table 3: Stages of nest construction according to Crook [2].

Stage	Wad stage (2 days)	Advanced wad stage	Ring stage (5 days)
Illustration			
Knots used			
Description	<p>The bird ties the first either to a palm leaf making a hole in it or to a hanging branch, forked or not. If the branch is forked (the most common case), it weaves strands around each element formed by the Y. Thus, the nest and the branch are completely interdependent and move together. If the branch is straight, it must first make a small notch or use a defect in the branch to hold the first strand. Baya's weaver then makes a bundle, a ribbon in the shape of a circle that will serve as a perch to tie the other strands without having to fly in static around his nest.</p>	<p>Continuous addition of strands extends the wad downwards while increasing the thickness and length of the ribbon that serves as a support. It then braids two horn-shaped protrusions on either side and connects them at the ends, forming a ring around himself.</p>	<p>It braids around the ring to widen it and add an opening downwards. The base of the nest is then made up of a first rather thick ribbon forming a temporary scaffolding during the construction. The base of the ring will then divide the chamber into two equal halves.</p>
Stage	Helmet stage (6 days)	Padded helmet stage	Completion (3 days)
Illustration			

Knots used		
Description	<p>The bird, perched in the initial ring, adds, strand by strand, material to the back edge of the upper part of the ring to make a flange that will form the roof of the egg chamber. At the same time, the front edge is also enlarged forming a porch-shaped roof that will later become the roof of the antechamber. Two openings are made in the ring: one for the entrance tunnel and the other to access the egg chamber. The shape of the nest then evokes that of a helmet.</p> <p>The male then calls, through whistles, the females which inspect all the nests by making them pass strength tests, pushing on the walls with their beak and pulling on fibers to check the quality of the work. The female then chooses the best nest, the builder of this one becoming her companion. At this stage, the male has designed and structured the egg chamber.</p> <p>Waiting for a female, the bird pads the exterior and interior surfaces increasing the thickness of the walls and strengthen the attachment point.</p>	<p>As soon as a female accepts a nest at the helmet stage (whether padded or not), the male spreads the wall of the egg chamber downwards and then braids the bottom (one day's work). It still pads the inside while the female brings a sparse lining of fibers and a few feathers that make up the floor of the egg chamber. The eggs can then be laid. They add drops of mud, clay or cowpat to the walls, perhaps in order to ballast the nest against the wind. During this time, and for two days, the male adds a long vertical tubular tunnel that will protect the entrance from rodents.</p>

5.1.2. Study of the nest and comparison with the BAYA algorithm's results

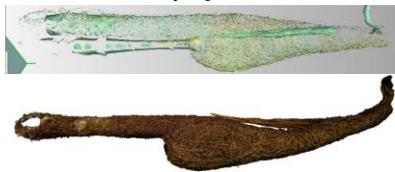


Figure 28: Nest modeling by laser surface scanner and by photogrammetry. François Goussard and Delphine Brant, researchers at the National Museum of Natural History.

Thanks to the color saturation and the bump pattern obtained, we have built an image recognition algorithm able to isolate on the nest surface most of the strands and recognize their diameter. We deduced the main directions and the density of the strands on each area of the nest. The results seem to betray the ghost of the temporary scaffolding used by Baya weaver to build its nest from the ring stage. To confirm this, we scanned the nest with X-rays thanks to the help of Dr. J.-R. Blondeau, head of Pont-l'Abbé hospital's radiology dept., and accessed to the interior of the nest's walls.

The objective of this part of the study is to answer the following question: does the Baya weaver follow, when it makes its nest, the laws of optimal weaving that we have defined? To answer this question, we have first carried out a survey by laser surface scanner and by photogrammetry of the nest with the support of Ph.D. Professor François Guéna, Scientific Director of the

MAP-MAACC laboratory and

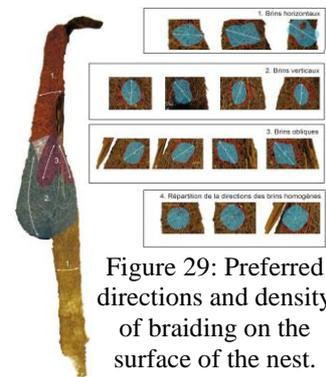


Figure 29: Preferred directions and density of braiding on the surface of the nest.



Figure 30: Sections of the RX scanner, reconstructed 3D model compared with predictions of BAYA algorithm.

This study enlightens the static scheme of the weaver's nest, which functions as a "swing" with the two sides perpendicular to the entrance hole being much more stressed. The braiding of the nest, which follows broadly that of its temporary perch, is not only justified by the construction's method: it is also the most efficient structural scheme for the object. This is confirmed by the striking proximity between the ideal nest braid provided by the BAYA algorithm and the one actually made by the bird. This study proved of the relevance of the optimal braiding laws and of the BAYA algorithm, and helped to determine the final static scheme of our project.

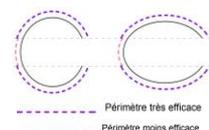


Figure 31: More stressed zones of the nest, as predicted by the BAYA algorithm.

5.2. Form finding: the drop of water and the weighted down stocking

Several authors compare Baya weaver’s nest to the shape of the drop of water at the time of its detachment. Others, like Newton, prefer the comparison with a suspended and weighted down stocking. These two forms have however their specificities, for some similar to our object of study, for others departing from it. The suspended stocking, like the nest and our architectural project, is punctually loaded by vertical forces directed downwards. However, its surface is a weaving, i.e., unlike our braid, it cannot bear any tensile stress, explaining why the free volume inside is greatly reduced. The water drop has a synclastic and stretched surface, coming from a field of pressure forces, that differs from that of the nest.



Figure 32: ideal shape from a form finding led on a Baya weaver's nest.

Thus, we carried out a comparative form finding study, looking for the shape minimizing the energy involved on the two systems using the BAYA algorithm. A spherical shell held at its summit vertex, modeled by mesh in taction only and without diagonals, submitted to a hydrostatic force field converges to the shape of a water drop. The distance of this shape to the Baya weaver's nest is 91.54%. But a very flexible spherical shell, without compression forces, forced to keep a constant volume at the bottom, and subjected to a vertical force field, converges to the shape of a weighted stocking. The proximity to the nest is 97.02%, which is therefore better, ruling in favor of Newton. It is only slightly less good than the shape which best describes the nest, obtained by reactivating the shell’s possibility to bear compressive forces (97.34%). This study helps us to decide on the ideal shape of our project.

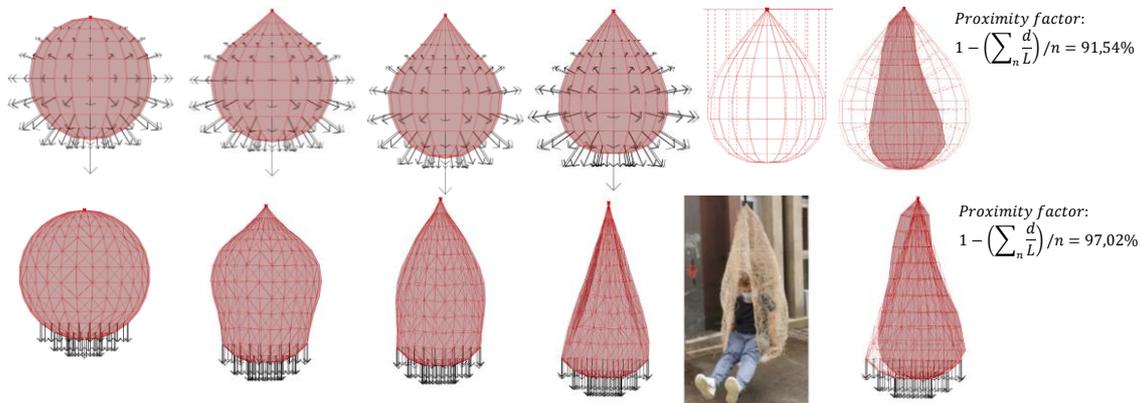


Figure 33: Form finding studies on a model of water drop and on a model of weighted stocking, results are compared with a 1:2 physical model.

5.3. Baya Project: application to a suspended pavilion at human scale

5.3.1. Context

The park of the Butte du Chapeau Rouge, developed from 1938 by Léon and Jean Azéma, is in the 19th district of Paris. After various tests comparing numerical and model studies, we opted, following the example of the colonies of nests of Baya weavers, for the realization of several pavilions implanted in the *chemin de ronde*, a peripheral walk below the esplanade, lined with lime trees and plane trees.

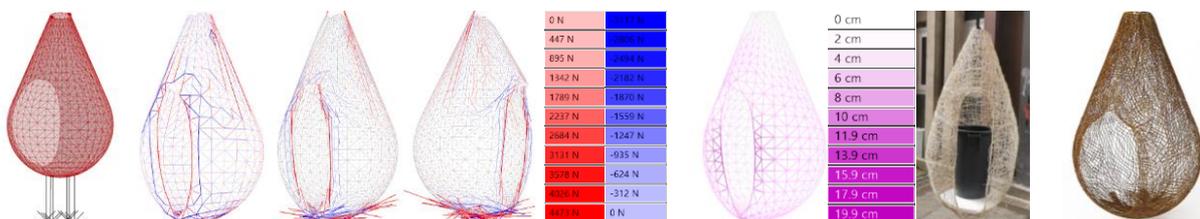


Figure 34: BAYA algorithm results on the project, displacements are compared with a 1:2 scale model.



Figure 35: Sketches, photomontage, 3D and fabrication of the Baya project.

Before braiding the final pavilion, we decided to build a 1:2 prototype. The deformation of the prototype was critical but fitted the algorithm prediction. The observation of the loaded surface guided us to reinforce the density of the compressed area in order to avoid surface buckling.

6. Conclusions

The outcomes achieved so far are:

- Obtaining the optimal braiding laws
- Algorithm for braiding the shells

Outcomes expected during next steps:

- Construction of the project Baya.
- Going on experimental verifications.

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